India's Tryst with Next-Gen Nuclear Energy Systems

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Abstract: *India’s advancing breeder reactor program, and the planned Advanced Heavy Water Reactor, both relying on domestically available thorium, will herald the era of next-generation nuclear energy systems in the country. With many embedded distinctive features, they would address effectively India’s energy security and safety concerns, while registering their novelty in the global nuclear discourse.*

The Indian nuclear establishment is **reportedly** in the final throes of developing a *(conceptual)* design for Advanced Heavy Water Reactor (AHWR), a Technology Demonstrator Reactor of 300 MW, as the stepping stone to the third stage of India’s three-stage nuclear energy program. In December 2016, Government of India is known to have accorded **in-principle approval** for the Tarapur Maharashtra Site (TMS) for locating the 300MW AHWR. Meanwhile, the 500MW Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, under construction for several years, is now **scheduled to be commissioned** towards the end of this year. These two developments (PFBR and AHWR) as they mature would herald the era of next-generation reactor systems in India. More importantly, India would be the first country, after Russia, to bring online a commercial fast-breeder reactor.

After the Indo-US nuclear deal was struck, though India has embarked on a nuclear energy expansion route with substantial progress especially on reactor capacity building, its success with the fast-breeder system is a significant achievement and milestone in India’s tryst with safe, secure and sustainable nuclear energy. Meanwhile, the AHWR program, when it matures, would *“**provide the impetus** for the development of technologies for the third stage of India nuclear power program” along with wide “experience on the use of thorium fuel on a large and industrial scale.”* With the aim of **universal electrification** with 24x7 electricity and double digit economic growth in the era of energy crisis, while reducing emissions intensity by 33%-35% by 2030, the **utilization** of abundantly available thorium is a viable option for India in the long-term.

Three-Stage Program

With a foresight to meet India’s future energy demand from perennial source, the visionary nuclear scientist Homi Bhabha had delineated a three-stage route for the country. The first stage, which mainly comprises the Pressurized Heavy Water Reactors (PHWRs), uses the domestic natural uranium as fuel to generate electricity. Currently, a total of **18 PHWRs** of 100 MWe to 540

MWe range capacity are in operation. In May 2017 the government **approved** construction of 10 more units of 700 MWe PHWRs.

In the first stage, natural uranium (U235, 0.72%) undergoes fission and a portion of the remaining U238 gets converted to Pu239; the spent fuel generated from this stage will be ***"reprocessed to recover"*** the Pu239, to be utilized as fuel in the Fast Breeder Reactors (FBRs) in the second stage. The **essence** of the *'process to reuse'* nuclear strategy is that it avoids both the buildup of stockpiles as well as the need to store large amounts of spent fuel that could be prone to malefactors. These reactors, *"besides using Pu239 as fuel, will also make use of* ***thorium as a blanket*** *in the reactor core. The thorium (Th232) will undergo nuclear mutation in the reactor core to produce U233."*

As part of the **Second Stage**, India started with the Fast Breeder Test Reactor (FBTR) at IGCAR, Kalpakkam. Operating with indigenously developed mixed (U+Pu) carbide fuel, the FBTR has provided required operating experience for designing the 500 MWe PFBR to utilize plutonium and the depleted uranium from our PHWRs. In the long-term, this would help *"to* ***make optimum use*** *of India's vast thorium reserves for sustained power generation to cater to the long-term needs of the nation."*

The good **performance** of India's FBTR operating since 1985 provided valuable operating experience and technical inputs which have been handy in fructifying the commercial PFBR stage. Four more PFBRs have been **announced** for construction by 2020. With the progress in the AHWR, India's nuclear energy program will enter the third stage of operation. This mammoth program has the potential to provide energy security to the country for a **few centuries**. As domestic supply is meager, **India imports** about 40% of its uranium requirements. The volatility of uranium market and the politics involved in its procurement necessitates expediting India's thorium-based program.

Novelty of Indian AHWRs

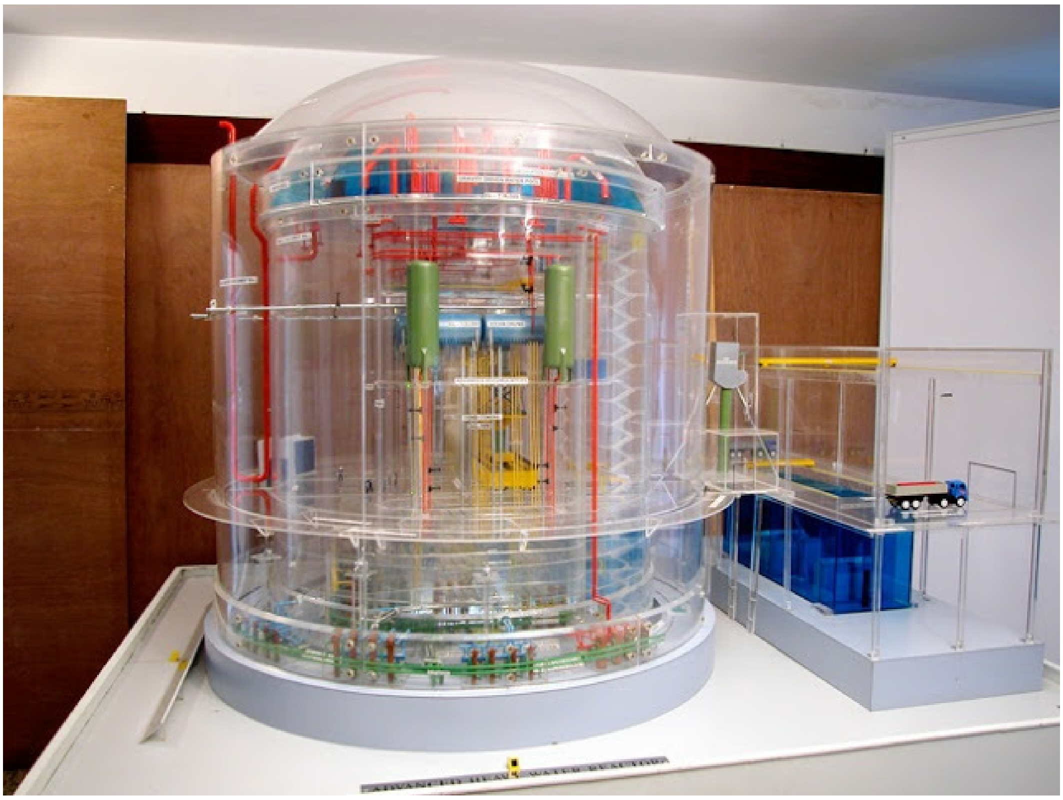


Image Attribute: Model of Advanced Heavy Water Reactor, the latest Indian design for a next-generation nuclear reactor / Source: Bhabha Atomic Research Centre (BARC), Department of Atomic Energy(DAE),Government of India

In general, the novelty of AHWRs includes, among other things, its advanced and innovative safety features, intrinsic proliferation resistance, cost-effectiveness, and efficiency. Given the concerns of nuclear accidents especially after the Fukushima accident, AHWRs are endowed with all such **techniques and arrangements** that can address postulated threats, both on design basis and beyond design basis. Therefore, it will **not require** an *'exclusion zone'* beyond the plant boundary.

Particularly, with double containment and a passive system for containment isolation, the Indian AHWR300-LEU will be extremely safe. First, *"the use of* ***heavy water (as moderator) at low pressure*** *reduces the potential for leakage"*, and **natural circulation technique (passive means)** is used for removal of heat from the reactor core under operating and shutdown conditions. *"Gravity Driven Water Pool with an inventory of 7000m3 of water is to be located near the top of the reactor building to remove heat from the core by natural circulation"*. In addition, there is an inherent advantage of using **high-pressure boiling water as coolant** to eliminating the requirement of steam generators.

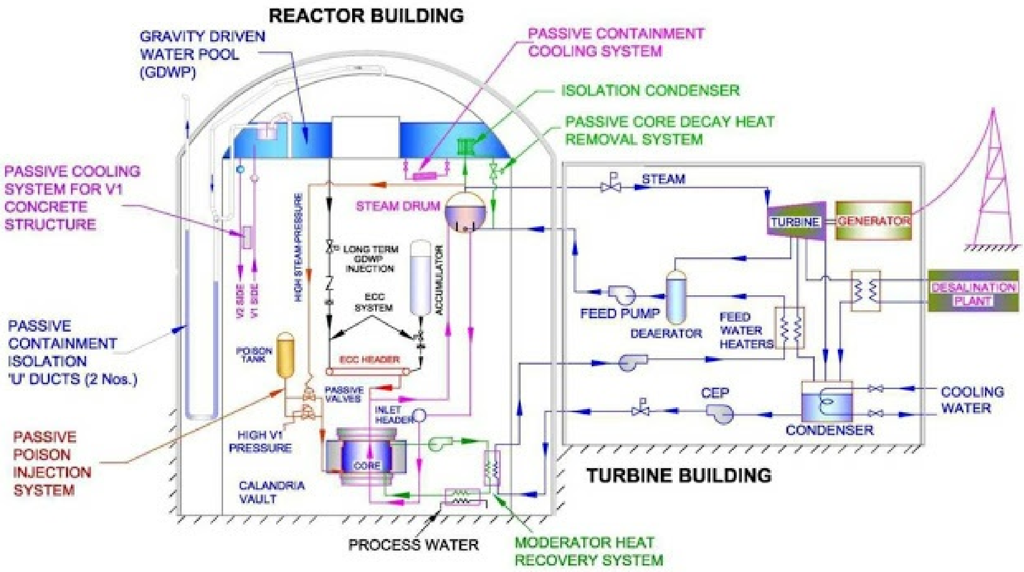


Image Attribute: Block Diagram of Advanced Heavy Water Reactor (AHWR)

The other planned **advanced safety features** include the provision of two independent shutdown systems (primary and secondary), passive poison injection in moderator in the event of non-availability of both the shutdown systems, making it disaster immune. In terms of reactor physics design, the AHWR300-LEU is based on *"negative **reactivity coefficients**"*, optimized to achieve high burn-up with the LEU-thorium based fuel with sufficient reactivity for an assured shutdown of the reactor under all accidental conditions.

As far as its efficiency is concerned in comparison to modern Light Water Reactors (LWRs), the AHWR300-LEU requires about **13% less** mined natural uranium for the same quantity of energy produced, thus making it a favorable option for efficient utilization of available natural uranium. The reactor is configured to obtain a significant portion of power by fission of U233, derived from in-situ conversion from Th232. On an average, **about 39%** of the power is obtained from thorium.

More importantly, the AHWR300-LEU is considered intrinsically proliferation resistant as it will use LEU and thorium that will lead to the **reduced generation of plutonium** in spent fuel with lower fissile fraction and a high fraction of Pu238. The fissile uranium in the *"spent fuel amounts to about **8%** and it also contains about **200 ppm of U232**, whose daughter products produce high-energy gamma radiation."* As bred uranium from Th (U232, U233, etc.) is mixed with U-238 of LEU (called denatured uranium), the system is automatically proliferation resistant.

As far as amicable disposal of the nuclear waste is concerned, the planned AHWR300-LEU seems most desirable as *"the Fast reactors operated in a closed fuel cycle help to improve the utilization of resources — both fissile and fertile materials — used in nuclear fuels and contribute to a significant **reduction of the burden** of generated radioactive waste."* As the quantity of minor actinides in thorium is less, the AHWR produces significantly **less minor actinides** per unit energy. Moreover, thorium oxide is eminently *"suitable for **long-term storage** because of the inert nature of the matrix."*

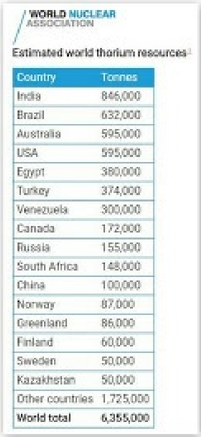
Furthermore, India's planned AHWR300-LEU, with many advanced features, is expected to reduce environmental impact, capital, and operating costs. With hundred years design life, it can prove to be akshaya patra, *"the mythical goblet with the **never-ending supply** of food."*

The Global Tryst

In the past, many countries laid their hands on the breeder reactor technology but ultimately gave it up. The United States of America discarded reprocessing of nuclear waste altogether. **Japan** and France (Superphenix reactor from 1985-98) could not handle liquid sodium and **failed** in its commercialization. China, though has a fast-breeder program, is believed to be more **than a decade behind**; construction of the Chinese Demonstration Fast Reactors (CDFR) started in 2013 and commissioning is expected in **2018-19**.

Only Russia could successfully run commercial fast-breeder reactor named **BN 800** (a successor of BN-600 in operation at the Beloyarsk NPP since 1980) that uses both uranium and plutonium as fuel. It is also **planning** to design a 1200 MW fast breeder reactor.

Thorium as Future



WORLD NUCLEAR ASSOCIATION

Estimated world thorium resources

Country	Tonnes
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	**6,355,000**

Chart Attribute: Global Thorium Deposit / Source: World Nuclear Association

Given the prospects of these systems, it would not be an exaggeration to assert that thorium is the key to meeting the burgeoning energy requirements of the entire world; *"thorium is more abundant in nature than uranium."* According to the IAEA-NEA publication Uranium 2014, the world's total thorium reserves amount to 6,355,000 tonnes and **India tops the list** with 846,000 tonnes alone. Moreover, there is **plenty of scope** for the use of thorium both in conventional reactors and prospective nuclear systems that are in the conceptual stage currently. They include solid fuelled conventional reactors; molten salt reactors; accelerator-driven subcritical reactors, etc. Though the **global uranium reserve** of 5,718,400 tonnes can meet the energy requirement of the entire world for the next several decades, it is not devoid of technological risks and geopolitical vagaries.

Especially for India, thorium is available in abundance and it is relatively easily obtainable than uranium which is short supply (**184,964 tonnes**, 2012). Though new reserves have been found in the state of Andhra Pradesh in the volume of **1,04,042 tonnes** (2017), mining them has been difficult for various reasons including the strong local opposition. Reportedly, from 2008 till mid-2016, around **5,559 metric tonnes** of uranium has been imported by India from different countries, costing the national exchequer and intense political-diplomatic attention.

In contrast, thorium is **available abundantly** in India in the Monazite sands of many Indian states like Odisha, Andhra Pradesh, Tamil Nadu, Kerala, West Bengal and Jharkhand. As they are easy to access, the thorium-based program, along with the advantage of overcoming waste disposal, would end India's dependency on the global uranium market in the long-run.

A Prognosis

Despite the promising future of thorium-based nuclear systems, critics point to several inherent drawbacks. First, though uranium is in short-supply, the post-Fukushima uranium market is not very competitive. Uranium is still available or supplied in plenty by many countries, especially in India after the Indo-US nuclear deal. Secondly, thorium-based programs have been discarded by many countries as they are expensive and **time-consuming.**

Skeptics believe that *"the likelihood of a rapid expansion of nuclear power"* in India is *"**very dim**"* The **goal post** of the three-stage program (and PFBR) has been shifted several times, and the final shape of the planned AHWR300-LEU is definitely far away; in the worst case, it may not fructify at all. Since the thorium utilization in FBR is a long way off, the AHWR was designed to give a quick start for the technological developments of thorium cycle.

Supporters, on the other hand, highlight the technological advantages of using thorium which will outweigh the perceived disadvantages. In any case, thorium is the most sustainable source of energy when no other easy options are available to the world.

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